# Geochemical Investigation of Fluid Involvement in Exhumed Faults of the San Andreas System: Collaborative Research with Texas A&M University and Saint Louis University

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Annual Project Summary

Frederick M. Chester
Department of Geology and Geophysics
Texas A & M University
College Station, TX 77843-3115
Telephone: (409) 845-3296; FAX: (409) 845-6162
E-mail: chesterf@geo.tamu.edu

David L. Kirschner
Department of Earth and Atmospheric Sciences
Saint Louis University
3507 Laclede Avenue
St. Louis, MO 63103
Telephone: (314) 977-3128; FAX: (314) 977-3117
E-mail: dkirschn@eas.slu.edu

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## Investigations Undertaken

Many models have been proposed to account for the weak-fault behavior of large strike-slip faults in the San Andreas system. Fundamental to many of these models are the physical and/or chemical role(s) of fluids. In addition, several models have been proposed that invoke chemical and mechanical effects of fluids in the nucleation, propagation, and arrest of seismic ruptures. These models envision significantly different sources, quantities, compartmentalization, and residence times for fluids in seismogenic fault zones. On the basis of existing data, it is difficult to discern which model(s) most accurately describes the fluid-rock interaction in faults and the role fluids play in the seismogenic cycle. This difficulty is due, in part, to the very limited amount of geochemical data that is presently available for faults of the San Andreas system. Study of the mineral phases, the major and trace element chemistry, and in particular, the stable isotope geochemistry of rocks in fault zones is one of the most effective tools to document fluid-rock interaction. At this time, however, only a few geochemical studies have been conducted on fault rocks in the San Andreas system.

It is the goal of this study to determine the extent of fluid involvement in the seismogenic cycle and to discern which model(s) most accurately describes fluid-rock interaction in large strike-slip faults of the San Andreas system. This will be accomplished through an integrated structural-geochemical study of fault rocks exposed in the two most deeply exhumed, large-displacement faults in the San Andreas system. The structural analysis will provide the requisite control that is so vital for collecting samples for geochemical analyses and interpreting the geochemical data in relation to the seismogenic cycle. The geochemical portion of the study will characterize the mineral phases, the major and trace element chemistry, and the stable isotope geochemistry of the fault rocks and adjacent host rocks. The results from the geochemical analyses, especially the stable isotope analyses, will better constrain the fluid-rock interaction in fault zones than is possible with the current data.

Over the contract period of FY99 we have collected and begun geochemical analysis of approximately 70 samples from the core and damaged zone of the San Gabriel fault at Bear Creek. In conjunction with sampling, we have finished a detailed (1:5) map of the sampled region (approximately 20 $m^2$). We have continued with geochemical analysis and modeling of the suite of approximately 70 samples collected from along the Punchbowl fault in FY98 to determine the fluid-rock interaction there. In addition, we have produced a new map of the core of the Punchbowl fault at a scale of 1:20 covering a region of approximately 40 $m^2$. The following summarizes our findings regarding the distribution of slip within the faults. The results of the geochemical analysis will be reported at a later date.

## Results

*Faults Studied*

The San Gabriel and Punchbowl faults are abandoned strands of the San Andreas fault system in the San Gabriel Mountains, California (e.g., Dibblee, 1968). The North Branch San Gabriel fault offsets igneous and metamorphic rocks 16-21 km in a right-lateral strike-slip sense. The fault is exhumed to several km depth and displays little evidence of dip-slip reactivation (Chester et al., 1993). In the Devil’s Punchbowl Los Angeles County Park area, the Punchbowl fault juxtaposes crystalline basement and arkosic sandstone of the Punchbowl Formation. The fault is exhumed to 2-4 km depth and records 44 km right-lateral separation (Chester & Logan, 1986). By analogy with nearby active faults, we assume that these faults were seismogenic and that the structure records the passage of numerous earthquake ruptures.

*Fault Internal Structure*

Both faults display a zoned internal structure of a fault core bounded by a broad damage zone (e.g., Chester et al., 1993). The damaged zone is on the order of 100 m thick and is characterized by fractured host rock and protocataclasite. There is a decrease in deformation intensity away from the core, and the damage at the boundaries is gradational with the host rock. Meso- and micro-fabrics indicate that the faults were extremely weak analogous to the modern San Andreas fault.

The fault core is meters-thick and contains cataclasite (often foliated) and ultracataclasite. The core is characterized by a greater degree of mineral alteration and density of veins than in the damaged zone. Primary igneous and metamorphic structures of the host rock are obliterated. Fault-parallel fabrics in the core record large shear strain. The ultracataclasite occurs as a central layer of the core and always contains a continuous and quasi-planar prominent fracture surface (pfs).

*Structure of the Punchbowl Fault Core and Ultracataclasite at Devil's Punchbowl*

Although primary structures of the host rocks are greatly disrupted towards the ultracataclasite, fabrics indicate almost all shear displacement on the fault occurred within the decimeters-thick layer of ultracataclasite. The contact of the ultracataclasite and surrounding cataclasite are extremely sharp, but not parallel or planar on the meter-scale. On the basis of color, cohesion, fracture and vein fabric, and porphyroclast lithology, two main types of ultracataclasite are distinguished in the layer: an olive-black ultracataclasite in contact with the basement, and a dark yellow-brown ultracataclasite in contact with the sandstone. The two are juxtaposed along a continuous contact that is often coincident with a single, continuous, nearly planar, prominent fracture surface (pfs) that extends the length of the ultracataclasite layer in all exposures. We infer that the pfs is a slip surface. The ultracataclasites are cohesive throughout except for thin accumulations of less cohesive, reworked ultracataclasite along the pfs. Structural relations suggest that: 1) the black and brown ultracataclasites were derived from the basement and sandstone, respectively; 2) the black and brown ultracataclasites were juxtaposed along the pfs; 3) the subsequent, final several kilometers of slip on the Punchbowl fault occurred along the pfs; 4) earthquake ruptures must have followed the pfs with only rare branching or jumping to other locations in the ultracataclasite (Chester & Chester, 1998).

Recently we have identified and mapped a section of the Punchbowl fault core that records branching of the pfs into the cataclastic rock bounding the ultracataclasite layer (Figure 1). Slip on the branch displaced a 0.5 x 2 m sliver of cataclasitic granite and gneiss into the ultracataclasite layer. Displacement of the sliver was accommodated in the bounding cataclastic host rock by offset on a network of antithetic and synthetic subsidiary faults. The older, blocky, yellow-brown ultracataclasite is preserved between the sliver and the sandstone. After branching, a single planar, continuous pfs was re-established and the sliver was displaced with the sandstone host rock. Trails of younger, flaky ultracataclasite derived from the sliver records localized slip and attrition wear along the boundary of the sliver and along the re-established pfs.

*Structure of the San Gabriel Fault Core and Ultracataclasite at Bear Creek*

The overall structure of the San Gabriel fault core at Bear Creek (Figure 2) is similar to that of the Punchbowl fault. Foliated cataclasites derived from the neighboring damaged host rock bound the ultracataclasite layer. There is a progressive increase in deformation and alteration towards the ultracataclasite. The orientation of cataclastic foliations and subsidiary faults are consistent with distributed right-lateral shear. The contact between the ultracataclasite and the bounding foliated cataclasite is sharp. Cataclastic foliations are truncated at the contact with the ultracataclasite.

A single, planar prominent fracture surface (pfs) occurs within the ultracataclasite along the entire length of the outcrop, and all contacts and surfaces either merge with or are cut by the pfs (Figure 2). Mapping reveals that several distinct types of ultracataclasite are present in the fault core. The ultracataclasite occurs in discontinuous layers that are sub-parallel to the pfs. Cross cutting relations may be used to infer the relative timing of ultracataclasite formation. The youngest ultracataclasite occurs along the pfs.

The structural relations in the San Gabriel fault core indicate that the formation of the foliated cataclasites and the localization of slip to a discrete surface occurred extremely early in the faulting history. The ultracataclasite layers were produced by attrition wear and accumulation of wear product along the slip surface. The slip surface was a long lived and relatively stable feature, and earthquake ruptures likely followed the pfs closely. Similar to that in the Punchbowl fault, there is evidence for branching of the slip-surface into the bounding cataclasite.

*Evolution of Ultracataclasite and Slip Surfaces*

On the basis of the structure of the San Gabriel and Punchbowl faults, we conclude that: 1) The fault cores consisting of foliated cataclasite, ultracataclasite and a continuous slip surface formed very early in the faulting history; 2) Most displacement was achieved by slip on a single, discrete, planar, continuous surface; 3) Attrition wear along this surface produced the uniformly fine-grained ultracataclasite that accumulated along the surface (Figure 3); 4) The slip surface was long-lived and stable, and more ancient structures away from the slip surface were relatively undisturbed by subsequent fracturing and shear; 5) Branching or jumping of the slip surface to new locations was a relatively rare event and, after it occurred, a planar slip surface geometry was re-established (Figure 4); 6) Reworking of existing ultracataclasite was common and occurred along the slip surface; 7) Addition of new material to the ultracataclasite by comminution of the host rock occurred where the host rock was in direct contact with the slip surface.

*Implications for Earthquake Slip Processes*

Assuming that the San Gabriel and Punchbowl faults slipped seismically, earthquake slip must have occurred along the principal slip surface with little branching or jumping of the earthquake rupture. The maintenance of the slip surface and the confinement of slip to that surface implies the surface was extremely weak over the life of the fault. The weak slip surface is consistent with evidence that the San Gabriel and Punchbowl faults, and other faults of the San Andreas system, are extremely weak (e.g., Zoback et al., 1987; Chester et al., 1993). In addition,

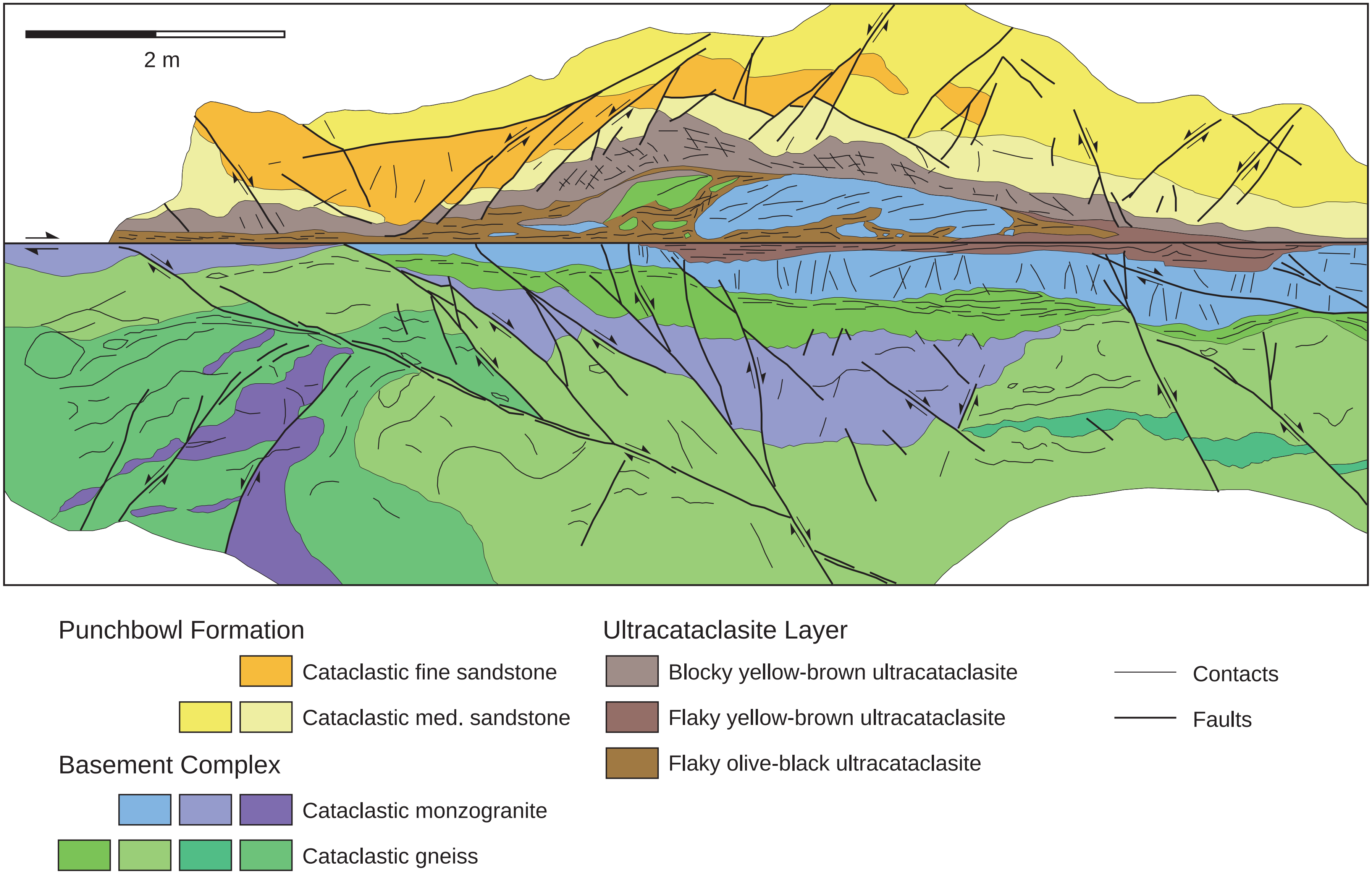


Figure 1. Map of the core of the Punchbowl fault at a location where the prominent slip surface branched and displaced a sliver of cataclastic host rock into the ultracataclasite layer. The prominent slip surface is shown as a thick black line. Note that a network of subsidiary faults is present in the cataclastic host in the vicinity of the sliver.

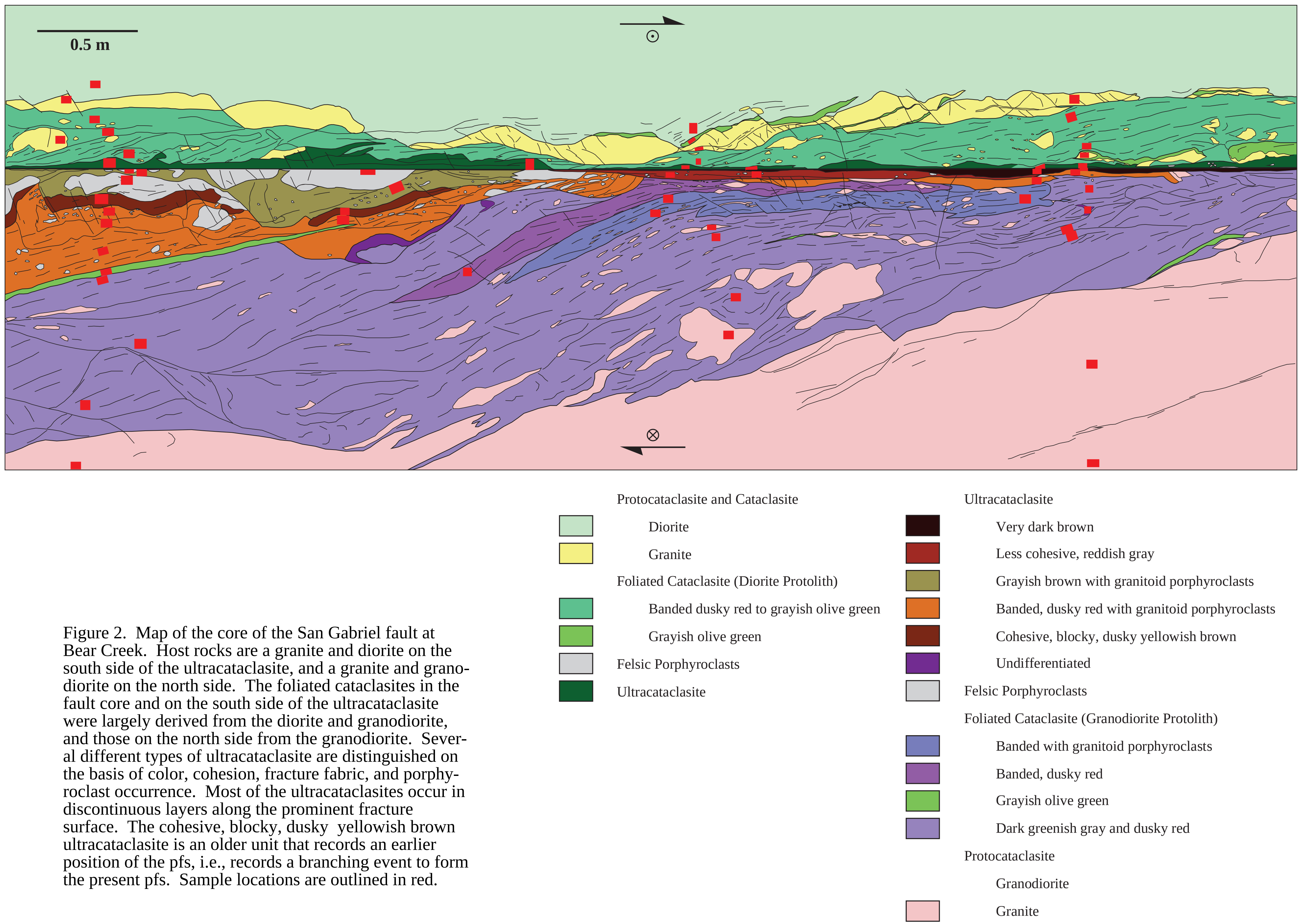


Figure 2. Map of the core of the San Gabriel fault at Bear Creek. Host rocks are a granite and diorite on the south side of the ultracataclasite, and a granite and granodiorite on the north side. The foliated cataclasites in the fault core and on the south side of the ultracataclasite were largely derived from the diorite and granodiorite, and those on the north side from the granodiorite. Several different types of ultracataclasite are distinguished on the basis of color, cohesion, fracture fabric, and porphyroclast occurrence. Most of the ultracataclasites occur in discontinuous layers along the prominent fracture surface. The cohesive, blocky, dusky yellowish brown ultracataclasite is an older unit that records an earlier position of the pfs, i.e., records a branching event to form the present pfs. Sample locations are outlined in red.

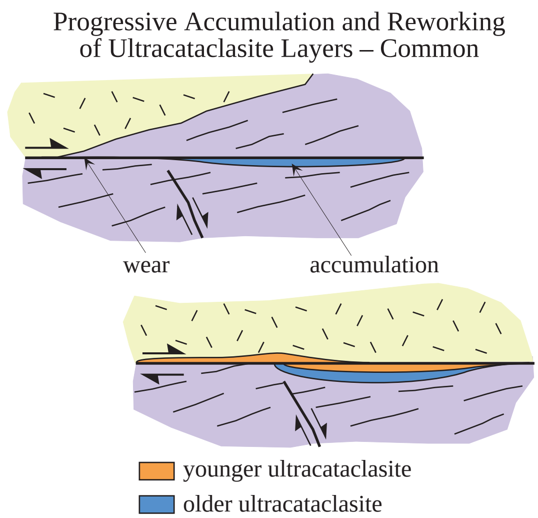


Figure 3. Proposed model for the production and accumulation of ultracataclasite along the principal slip surface. Locally, ultracataclasite is produced by attrition wear along some sections of the principal surface, and accumulates at other locations along the surface. Geometric irregularities and off-surface deformation, such as by subsidiary faulting, leads to uneven wear and accumulation. As a result of juxtaposition of different host rocks with slip, different types of ultracataclasite accumulate in layers along the surface. If the surface does not branch to a new location, the age of the ultracataclasite increases with distance from the surface.

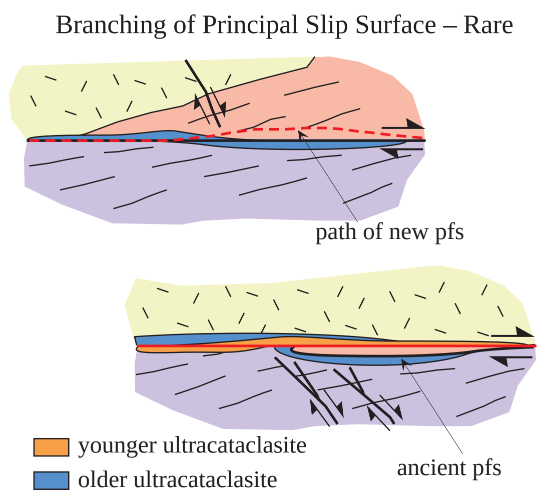


Figure 4. Proposed model for branching of the slip surface and incorporation of host rock into the ultracataclasite layer. By branching, a section of the principal slip surface and associated ultracataclasite is abandoned, and a new surface is formed. Apparently, subsequent deformation in the surrounding cataclastic host rock occurs and the newly formed slip surface re-establishes a planar geometry.

the morphology of the principal slip surface in the ultracataclasite is similar to the slip surfaces present in laboratory friction experiments. Accordingly, the frictional properties of the surfaces may be similar. In particular, the structure of the San Gabriel and Punchbowl faults is consistent with small critical slip distances and breakdown dimensions for nucleation and propagation of earthquake ruptures.

It is possible to use our observations to evaluate several hypotheses for weakening of the San Andreas and other large-displacement faults. The evidence of cementation and general preservation of structures in the ultracataclasite implies the rocks were cohesive for much of the faulting history. Only very minor fractions of the ultracataclasite could have behaved as an incohesive granular material during each fault slip event. Thus mechanisms of weakening that require distributed granular flow are not supported by our observations (e.g., Melosh, 1996; Herrmann et al., 1990; Scott, 1996). Other observations indicate that: 1) relatively little pressure solution occurred during faulting; 2) only minor fractions of the ultracataclasite are clay minerals; 3) there is little evidence for large fluid flux along the fault zone; 4) friction melting did not occur. The structure of the faults favor weakening processes consistent with extreme localization of slip but not with associated melting. We conclude that dynamic weakening by thermal pore-fluid pressurization (e.g., Sibson, 1973) and transient reduction in normal stress associated with pulse-like slip (e.g., Brune et al., 1993; Ben-Zion & Andrews, 1998) are possible mechanisms for weakening these faults, and by analogy, may explain the weakness of the modern San Andreas.

## Non-Technical Summary

Knowledge of how and why earthquakes occur is critical in our effort to reduce the loss of life and property as a result of natural hazards. The physical processes operating in fault zones leading to earthquake slip nucleation, propagation and arrest occur deep within the earth's crust and can not be studied directly. One of the primary means of investigating earthquake faulting processes is through careful study of ancient faults that are presently exposed on the earth's surface due to erosion of overlying material. We are using a variety of analytic techniques to study the earthquake process, with special attention being given to the mechanical and chemical interaction of pore fluid and rock during faulting. This field study provides information to guide future experimental and theoretical modeling efforts and to test current hypotheses of the faulting process. This and related work will ultimately provide a sound mechanistic understanding of the earthquake faulting process that will help us understand how and why earthquakes occur.

## Reports Published


Chester, F. M., Characterization of the Internal Structure of the San Andreas Fault at Depth Based on Study of Surface Exposures of Exhumed Faults, *Eos Trans. AGU*, *79*, F576, 1998.

Chester, F. M., D. L. Kirschner, and J. S. Chester, Extreme Localization of Slip During Earthquake Rupture - Field Evidence from the Punchbowl and San Gabriel Faults, San Andreas System, California, *Eos Trans. AGU*, *80*, F689, 1999.

Chester, F. M., D. L. Kirschner, and J. S. Chester, Structural and geochemical investigations of the Punchbowl fault, San Andreas system, California, in *Program & Abstracts of the International Workshop on Frontiers in Monitoring Science and Technology for Earthquake Environments*, Japan Nuclear Cycle Development Institute Publication, TW7400 98-001, 4 pp., Toki, Japan, 1998

Kirschner, D. L., and F. M. Chester, Are fluids important in seismogenic faulting? geochemical evidence for limited fluid-rock interaction in two strike-slip faults of the San Andreas System, *Eos Trans. AGU*, *80*, F727, 1999.

Kirschner, D. L., and F. M. Chester, Structural and geochemical investigation of fault rocks in the core of the Punchbowl Fault, San Andreas system, California, *GSA Abstracts w/ Program*, *30*, A324, 1998.

Wilson, J. E., J. S. Chester, and F. M. Chester, Microfracture fabric of the Punchbowl fault zone, San Andreas System, California, *Eos Trans. AGU*, *80*, F746-747, 1999.